Automaticity of access to numerical magnitude and its spatial associations: the role of task and number representation

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Abstract

Generally, people respond faster to small numbers with left-sided responses and large numbers with right-sided responses, a pattern known as the SNARC (spatial numerical association of response codes) effect. The SNARC effect is interpreted as evidence for amodal automatic access of magnitude and its spatial associations, as it occurs in settings where number is task-irrelevant, and for different number formats. We report five studies designed to establish the degree to which activation of magnitude and its spatial associations is truly automatic and amodal. Based on the notion of autonomous automaticity, we hypothesised that the mere presence of a number form (to which participants made a color decision) would be sufficient to elicit the SNARC effect. However, we found no evidence of a SNARC effect for simple color decisions to Arabic digits (Experiment 1). There was a SNARC effect for color decision to digits when participants recognised the stimulus as a digit before responding (Experiment 2), participants viewed the digit for sufficient time before color onset (Experiments 3 and 5), or there was temporal uncertainty regarding color onset (Experiment 3). There was no SNARC effect for color decision to arrays of circles (Experiment 4), regardless of viewing time or temporal uncertainty. Overall, our results suggest that, while access to magnitude and its spatial associations is not automatic in an "all-or-none" sense, it is certainly at the strong end of automaticity, and that this automatic activation is modality dependent. Our findings are most supportive of conceptual coding accounts of the SNARC effect.

Keywords: SNARC, digits, non-symbolic number, automaticity

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What are the processes that underlie our perception of numerical information and our understanding of numerical magnitude? One repeated finding that has informed accounts of numerical cognition is that people are generally faster to respond to small quantities with a left-sided response and to large quantities with a right-sided response; the Spatial Numerical Association of Response Codes (or SNARC) effect (Dehaene, Bossini, & Giraux, 1993; for reviews see, e.g., Fischer & Fias, 2005; Gevers & Lammertyn, 2005; van Dijck, Ginsburg, Girelli, & Gevers, 2015). This finding strongly suggests that numerical magnitude and space are closely associated in human cognition and is consistent with findings from neuroimaging that suggest numbers and space are both subserved by structures within the parietal cortex (see e.g., Hubbard, Piazza, Pinel, & Dehaene, 2005 for a review); as such, it has been influential in the development of models of number processing. For example, when they first demonstrated the SNARC effect, Dehaene et al. (1993) attributed it to automatic access of a number magnitude representation akin to a “mental number line”.

In their original study, Dehaene et al., (1993) asked participants to make parity judgements to the digits 0 to 9 using left- and right-hand key presses. However, while the SNARC effect is driven by numerical properties, it is not restricted to settings where numerical information is directly relevant to the task. For example, Dutch participants who were asked to report whether visually presented Arabic digits contained the phoneme /e/ using left and right button presses showed a SNARC effect (Fias, Brysbaert, Geypens, & d’Ydewalle, 1996). There is also evidence of a SNARC effect for visual detection; Fischer, Castel, Dodd, and Pratt (2003) reported that participants responded faster to targets in the left visual field after viewing small digits (1 or 2) and faster to targets in the right visual field following larger digits (8 or 9). In a free viewing paradigm, Fernández, Rahona, Hervás, Vázquez, and Ulrich (2011) found that participants’ first eye movements were influenced by the magnitude of a preceding number such that they tended to look left following presentation of the numbers 1-4 and right following the presentation of 6-9. As a consequence of such findings, the SNARC effect is often described as “automatic”; for example, Fischer et al. (2003) concluded that “mere observation of numbers obligatorily activates the spatial representations associated with meaning” (p. 556). Likewise, Nuerk, Wood and Willmes (2005) reported SNARC effects for auditory number words, visual Arabic numerals, visual number words and visual dice patterns and concluded “the SNARC effect indexes the existence of an automatic pathway to an amodal semantic magnitude representation” (p.191). In a review of the literature, Fias and Fischer (2005) concluded, “a high degree of automaticity is involved in the processes that give access to the magnitude representation and its spatial association” (p.50).

The purpose of the current set of studies is to answer two questions that are encapsulated in the quotes above: to what extent is the pathway to magnitude truly *automatic,* and to what extent is it truly *amodal*? There are many individual SNARC studies that can be cited to provide evidence for or against automaticity; however, few of them systematically change individual elements of a task to directly compare whether or not it elicits a SNARC effect. Furthermore (as discussed below), discussion around automaticity and magnitude have generally been framed in an “all-or-none” fashion, when a graded distinction is more useful. With regards to the nature of number representation, there are very few studies (to our knowledge only one, Bulf, Macchi Cassia & de Hevia, 2014, discussed below) that have directly compared non-symbolic non-canonical representations of magnitude with symbolic representations of magnitude for SNARC where numerical properties were not relevant to the task. As a consequence, in the current series of studies, we aimed to directly compare SNARC effects for digits and non-symbolic number in order to establish the degree to which numerical representations are automatically accessed upon presentation of numerical information, and to establish whether this automaticity is influenced by the form of that information.

Defining automaticity

When a process is described as automatic, this gives rise to certain assumptions; for example, one might argue that automatic processing should be capacity free, should be immune to interruption from other parallel processes, should not rely on attention or conscious monitoring, and should occur without the intentional setting of the goal of the behaviour (e.g., Ganor-Stern, Tzelgov, & Ellenbogen, 2007; see, Moors & De Houwer, 2006, for a thorough analysis of automaticity; see, e.g., Ansari & Besner, 2005, for a discussion of automaticity with reference to digit processing). For example, Bargh (1994) listed “four horsemen of automaticity” as processes that are *efficient*, *unintentional*, *uncontrollable* and *unconscious*. Under an “all-or-none” approach to automaticity, a process would need to meet all of these criteria to meet the definition of automatic, but a more useful way to understand cognitive processes is to take a nuanced view of automaticity that is based on its different features (see e.g., Bargh, 1992; Hasher & Zacks, 1979; Logan & Cowan, 1984; Tzelgov & Ganor-Stern, 2005; Moors & De Houwer, 2006, for a review). For example, we can draw a distinction between processes that are *autonomously* automatic (i.e., occur regardless of whether they are part of the task requirement) and those that are *intentionally* automatic (i.e., processes that occur only when they are part of the task requirement, for detailed discussion see, e.g., Cohen Kadosh, Henik, & Rubinsten, 2008; Tzelgov & Ganor-Stern, 2005; Tzelgov, Henik, Sneg, & Baruch, 1996).

The SNARC effect does not fit neatly into either of these definitions. It does not meet the criteria for intentional automaticity, as it occurs for tasks where magnitude is not part of the task requirement (as in visual detection and phoneme monitoring, Fischer et al., 2003;

Fias et al., 1996). However, it does not meet the criteria for autonomous automaticity either, as it does not appear to occur for all tasks. For example, Zanolie and Pecher (2014) failed to replicate Fischer et al.’s (2003) visual detection results; across six experiments, the only conditions under which they found a SNARC effect were when participants had to make a magnitude decision (whether the digit they had seen was higher or lower than 5) after having performed the target detection task. In other words, the effect only arose when the participants had to retrieve the magnitude of the digit as part of the task, and Zanolie and Pecher concluded that “the mental number line is not activated automatically but at best only when it is contextually relevant” (p. 1). Other evidence suggests that the SNARC effect is associated with response selection rather than early perceptual processing, which would go against a strict interpretation of automaticity. For example, Müller and Schwarz (2007) used parity judgements in a psychological refractory period paradigm (see e.g., Pashler, 1994) and found that the effect likely arises during response selection rather than during perceptual encoding or response execution. This conclusion is backed up by findings in the event-related brain potential and lateralised readiness potential literature (e.g., Gevers, Ratinckx, De Baene, & Fias, 2006; Otten, Sudevan, Logan, & Coles, 1996).

Further evidence against strong automaticity comes from the fact that the SNARC effect appears to be susceptible to apparently minor differences between tasks. For example, Fias, Lauwereyns, & Lammertyn (2001) presented colored digits and shape stimuli superimposed onto irrelevant digits; participants were simply asked to respond to the color of the digits (Experiments 2 and 3), or to the form (circle versus square, Experiment 5) or orientation (triangle pointing upwards or downwards, Experiments 1 and 4) of the superimposed shape. Fias et al. found SNARC effects driven by the irrelevant number for orientation judgements, but not for color or shape judgements. Lammertyn, Fias and Lauwereyns (2002) again compared color decision with orientation decision, this time using colored digits and rotated digits; again, they found a SNARC effect for orientation judgements but no SNARC effect for color decision. In other words, mere exposure to a digit is not necessarily sufficient to prompt access to its semantic representations; other conditions or triggers must be present for numerical information to be accessed.

Moors and De Houwer (2006) argue that, while automaticity is useful as an “umbrella term” (p. 321), researchers need to be clear about the *sense* in which we believe a process to be automatic and which individual features of automaticity can be applied to that process. In order to do this, we need to establish the set of preconditions that must be in place before a process occurs. Currently, the degree of automaticity with which semantic information about a number is accessed has yet to be established; researchers have tended to focus on whether different tasks trigger the SNARC effect but have not systematically altered aspects of these tasks within the same series of experiments. A goal of the current studies was to investigate where on the continuum of automaticity the SNARC effect lies; as one of the only tasks for which SNARC effects appear *not* to occur, we therefore chose to use color decision as our baseline task.

(A)modality of magnitude representation

Numerical information can be represented in a multitude of ways. Fias and Fischer (2005) observed that this can include Arabic or Roman symbols, finger positions, dot patterns or number words, and noted that “if the SNARC effect indicates access to the abstract representation of number magnitude then it should be insensitive to these variations” (p. 47). However, as noted in the same volume by Tzelgov and Ganor-Stern (2005), number modality and format does appear to matter for some tasks. For example, Cohen Kadosh et al. (2008) reported that size congruity effects differed for Arabic and verbal numbers, and argued that there should be separate comparison mechanisms for verbal and Arabic numbers in models of numerical processing. In their original study, Dehaene et al. (1993) reported that the SNARC effect was weaker for verbal numerals rather than Arabic numerals, and argued that the representation of number magnitude (or a mental number line) is automatically activated only by Arabic numerals. Within the context of Dehaene’s (1992) triple-code model, which proposes three concrete representations for number (visual Arabic, auditory verbal, and analogue magnitude), they argued that the finding could be accounted for by postulating that Arabic-to-analogue transcoding is an automatic process while the verbal-to-analogue pathway is weaker.

Less is known about SNARC effects for non-symbolic, non-canonical number. Nuerk et al. (2005) reported SNARC effects for parity decisions to dice patterns; however such familiar canonical displays may offer participants a direct route to magnitude information that is not present for non-canonical displays, and the task requirement to retrieve parity status means that numerical information had to be accessed to perform the task. Patro and Haman (2012) and Ebersbach, Luwel, and Verschaffel (2014) found spatial-numerical associations with non-symbolic number in children but, again, these tasks required explicit processing of magnitude (e.g., indicating which of two plates of sweets had more or fewer sweets, Patro & Haman, 2012). Numerical distance effects have been reported for non-symbolic number such that people are slower and less accurate to decide which is the larger of two numbers or numerosities that are close (e.g., 2 items vs. 3 items) than when the distance is greater (e.g., 2 vs. 8; Moyer & Landauer, 1967), and it has been argued that such effects are driven by spatial associations with number; however, again, this is a task that requires explicit reasoning about magnitude. To our knowledge, there are only two reports of a SNARC effect for non-symbolic, non-canonical number when magnitude is task-irrelevant. The first was reported by Mitchell, Bull and Cleland (2012), who asked participants to indicate with left- and right-hand key presses whether arrays of one-to-nine triangles were presented pointing upwards or downwards. However, this finding has yet to be replicated. The second was based on Fischer et al.'s (2003) visual detection task; Bulf et al. (2014) presented participants with either the digits 2 or 9, or with two or nine circles presented centrally on a screen. This was then followed by a to-be-detected target presented on either the left or right of the screen. For both representations, participants were faster to detect a target on the right following larger numerical magnitudes and the left following smaller numerical magnitudes. Based on this finding, we would expect to see similar SNARC effects for digits and for arrays of objects. However, as noted above, others have failed to replicate the SNARC effect for visual detection with digits (Zanolie & Pecher, 2014). Furthermore, we know of no studies that directly compare performance on the same SNARC task for symbolic and non-symbolic, non-canonical information when semantic information about the number was irrelevant to the task and left- and right-handed responses are required.

The current studies

The current studies were designed to test two hypotheses about the SNARC effect: (1) that it reflects an *automatic* pathway to magnitude, and (2) that the representation of magnitude and its spatial association is *amodal*. In order to do this, we focussed on the color decision task for both digit and non-symbolic number, where participants were simply asked to indicate whether the stimulus on the screen was blue or green by making key presses with their left and right hands. In Experiments 1 and 2, we first investigated (1) whether we would replicate the null finding for SNARC effects for color decision to digits, and (2) whether the requirement to recognize the stimulus as a number prior to responding would be enough to trigger the SNARC effect. In Experiment 1, participants made color decisions to digits and Greek letters presented on a computer screen. Based on the findings of Fias et al. (2001), we expected there to be no SNARC effect for this task. However, in Experiment 2, we included an inhibitory go / no-go element to the task such that participants made color decisions to digits but withheld responses to the Greek letters. This manipulation meant that the participants had to recognise the stimulus *as a number* before proceeding to the color decision task. If we assume that simply recognising something as a number is enough to trigger access to the semantic associations with that number, we would predict a SNARC effect for this task. An analysis of the data from Experiment 2 was previously reported in another paper in the context of assessing whether or not different studies demonstrated a sex difference in spatial associations with number (Bull, Cleland, & Mitchell, 2013); however it was originally run as part of the current series of experiments and we report further detail and additional analyses here.

Following the finding of a SNARC effect in Experiment 2 (but not Experiment 1), our next step was to establish whether simple color decision could trigger a SNARC effect if we altered the timing of stimulus presentation to increase digit viewing time. To this end, in Experiments 3 and 4 we introduced three color onset conditions (0 ms, 200 ms, and 400 ms). In the 0 ms condition the stimuli were blue or green when they appeared on the screen, in the 200 ms condition the stimuli were presented in black for 200 ms prior to color onset, and in the 400 ms condition they were presented in black for 400 ms. The onset conditions were mixed across the experimental session. This tested the hypothesis that magnitude and its spatial associations are accessed automatically but relatively slowly. In Experiment 3, participants made their responses to digits, but in Experiment 4, we presented arrays of one to nine circles. This allowed us to test the hypothesis that the automaticity of SNARC effects should be similar regardless of the form of magnitude representation; if the SNARC effect is unaffected by the form of numerical representation, then we would expect the same pattern of results to occur across Experiments 3 and 4 regardless of the form of the numerical information. In fact, we found that participants showed a significant SNARC effect when responding to digits in Experiment 3, but no evidence of a SNARC effect when responding to arrays of circles in Experiment 4. Finally, in order to distinguish the role of temporal uncertainty regarding color onset versus digit viewing time, in Experiment 5, the 0 ms, 200 ms, and 400 ms conditions were blocked rather than mixed. If temporal uncertainty alone drove the SNARC effect in Experiment 3, we would expect to see no SNARC effect in Experiment 5; if viewing a digit for sufficient time played a role in eliciting the SNARC effect, we would expect to see no SNARC effect for the 0 ms condition, but a SNARC effect for the 200 ms and 400 ms conditions.

Experiments 1 and 2

Method

Participants. Forty participants (20 men, mean age 20.39 years, SD = 2.98) took part in Experiment 1 and 40 participants (20 men, mean age 21.58 years, SD = 5.84) took part in Experiment 2. All were either undergraduate or graduate students recruited on a voluntary basis or for course credit. All had normal or corrected-to-normal vision. All studies received ethics committee approval from the School of Psychology, University of Aberdeen.

Stimuli and Procedure.

Stimuli. In both experiments, the stimuli were blue and green digits (1-9, excluding 5) and Greek letters (Ω, Φ, β, δ, ζ, λ, ξ, and φ, simply described as “symbols” to the participants) presented onscreen in Arial font size 36.

Experiment 1 procedure. Participants were instructed that, on each trial (regardless of whether they saw a digit or a symbol), they should indicate whether the stimulus was presented in blue or green. Half of the participants responded to blue stimuli with the *M* key and green stimuli with the *Z* key; for the other half the response mapping was reversed. On each trial, a fixation cross was presented centrally for 1000 ms. This was then replaced by either a symbol or digit, which remained onscreen for 1500 ms or until the participant made a response. This was followed by a blank screen for 1000 ms before the fixation point for the next trial. The experimental session consisted of 240 trials in total; 192 of these were digit trials (24 presentations of each digit, 12 green and 12 blue), and 48 were symbol trials. The main experimental session was preceded by a practice block of 24 trials (16 digit trials and 8 symbol trials), with feedback on response time and accuracy. There was no feedback during the main experimental block. The experimental stimuli were presented on a Dell 19” flat panel monitor using a Dell PC running Windows XP, with key presses recorded from a Dell keyboard. Reaction times were collected using E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA).

Experiment 2 procedure. In Experiment 2, participants were instructed that if they saw a digit, they should indicate whether it was presented in blue or green. However, they were also instructed that they should withhold their response if the stimulus was a symbol. In all other aspects, the procedure was identical to Experiment 1.

Results

In all experiments, reaction times for each digit responded to with the left and right key were collated and the median time calculated (correct responses only). The difference in the time to respond to each digit with the right and left hand was then calculated (right hand RT – left hand RT). If there is a SNARC effect, then we would expect responses to smaller digits to be faster with the left hand than with the right hand, yielding a positive value when the reaction time for the left hand is subtracted from the reaction time for the right hand. At the other end of the scale, responses to larger numbers should be faster with the right hand, yielding a negative value when the reaction time for the left hand is subtracted. As a result, plotting the reaction time differences against number should yield a negative going slope. In order to quantify this, the nature of the SNARC effect was captured by regression analyses (Lorch & Myers, 1990, Method 3; for a detailed discussion, see Fias, Brysbaert, Geypens, & d’Ydewalle, 1996). A regression equation was computed for each participant, with digit magnitude as the predictor variable and reaction time difference as the criterion variable. In the absence of a SNARC effect, the reaction time difference across the digits should remain relatively constant and the regression weight (standardised β) should not differ significantly from 0. In the presence of a SNARC effect, we would expect to see a negative regression weight that does differ significantly from 0. As such, the regression weight was recorded for each participant, and a one-sample *t*-test conducted to determine whether the regression weights across participants differed significantly from 0 (a flat line). The mean response time differences for both experiments are displayed in Figure 1.

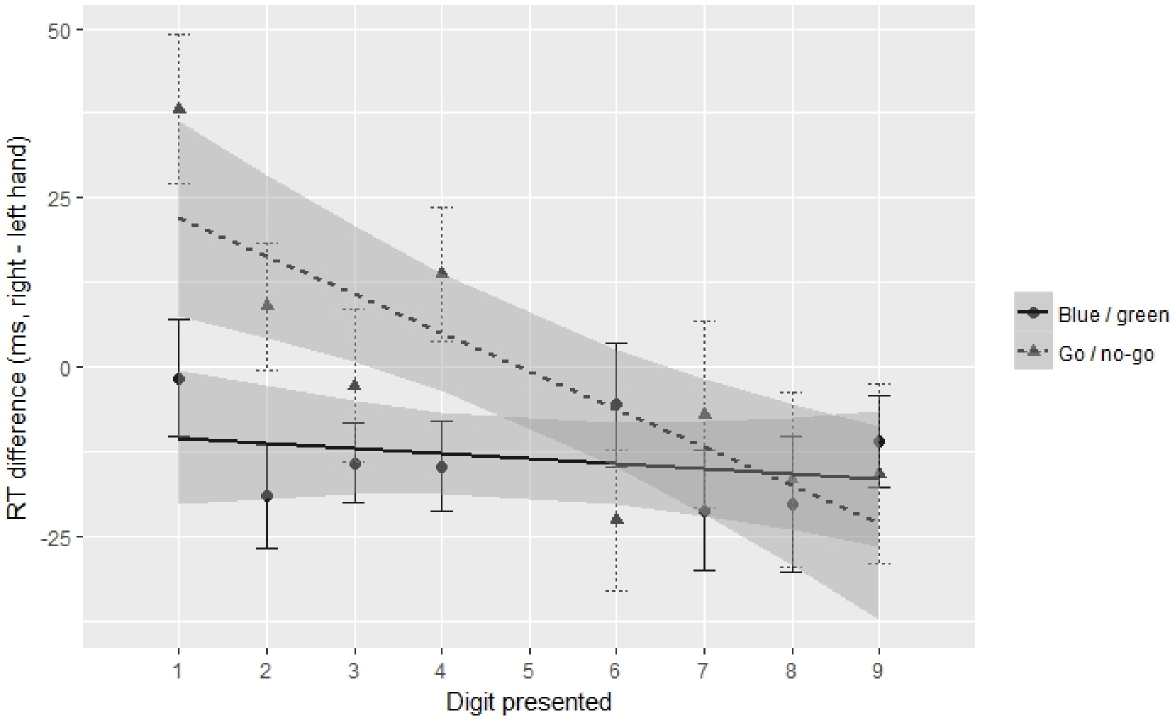

Figure 1. Mean reaction time difference for each digit for color decision in Experiment 1 (Blue/green: participants made color decisions on all trials), and Experiment 2 (Go / no-go, participants only responded to digits). Errors bars show +/- 1 standard error. The shaded area shows the 95% confidence interval for the trend line. All graphs were generated using ggplot 2 (Wickham, 2009) in R (R Core Team, 2016).

Experiment 1 Results. The mean error rate was 4.22%, with trials on which an error occurred excluded from the analysis. The mean reaction time for correct trials was 447 ms (mean reaction times across all studies are listed in Table 1).

There was no evidence of a SNARC effect; a one-sample *t*-test revealed that the regression weight did not differ significantly from 0, mean β = -.013, t (39) = -.224, p = .824, d = .035, 95% CI [-.133, .107]. Given that we are reporting null findings, we additionally ran a Bayesian one-sample *t*-test using a Cauchy prior width of .707 (see, e.g., Rouder, Speckman, Sun, Morey, & Iverson, 2009) using JASP software (JASP team, 2018). This yielded a Bayes Factor (BF_{10}) of 0.175, suggesting moderate evidence for the null hypothesis. We report Bayes Factors for the remaining *t*-tests in the paper, using the same Cauchy prior width in all cases.

A reviewer (Marc Brysbaert) suggested that we check whether a MARC effect (markedness association of response codes) masked an underlying SNARC effect in our data. To briefly summarise, the MARC effect refers to the fact that odd numbers are typically responded to faster with the left hand and even numbers with the right hand (e.g., Berch, Foley, Hill, & Ryan, 1999; Nuerk, Iversen, & Willmes, 2004; Reynvoet & Brysbaert, 1999). Importantly, the MARC effect has been shown to interfere with the SNARC effect (e.g., Berch et al., 1999; Zohar-Shai, Tzelgov, Karni, & Rubinsten, 2017). In order to rule out this possibility, we ran additional analyses in Experiment 1 to examine whether there was a MARC effect in our data. Following Zohar-Shai et al., we calculated median reaction time for each hand, and ran a repeated measures Analysis of Variance (ANOVA) with hand (left versus right), magnitude (1-2 versus 3-4 versus 6-7 versus 8-9) and parity (1-3-5-7 versus 2-4-6-8) as factors. There was a main effect of response hand, F (1, 39) = 13.986, p < .001, MSE = 2124, η_p^2 = .264, with responses for the left hand (455 ms) slower than responses with the right hand (442 ms). However, there were no other main effects or interactions. In particular, there was no reaction time difference between responses to odd (448 ms) and even (449 ms) numbers, and there was no interaction of parity by response hand, *F* (1, 39) = .335, *p* = .566, *MSE* = 992, η_p^2 = .009 . In other words, there was no evidence that an underlying SNARC effect was being masked by a MARC effect.

Experiment 2 Results. The mean error rate for "go trials" (i.e., color decision to digits) was 4.8% and for "no-go trials" (i.e., withheld responses to Greek letter trials) was 1.5%. The mean reaction time for correct trials was 511 ms. A one-sample *t*-test revealed that the regression weight differed significantly from 0, mean β = -.245, *t* (39) = -3.38, *p* = 0.002, *d* = 0.534, CI[-.391, -.098], BF_{10} = 19.486, indicating strong evidence against the null hypothesis.

As in Experiment 1, we additionally ran a repeated measures ANOVA with hand (left versus right), magnitude (1-2 versus 3-4 versus 6-7 versus 8-9) and parity (1-3-7-9 versus 2-4-6-8) as factors. This revealed a significant interaction of response hand by magnitude, *F* (3, 117) = 4.60, *p* = .004, *MSE* = 3058, η_p^2= .105. As one would expect given the significant SNARC effect in the regression analyses, reaction times for the left hand generally became slower with magnitude bin (509 ms for 1-2, 513 ms for 3-4, 524 ms for 6-7, and 523 ms for 8-9), while reaction times for the right hand generally became faster (532 ms for 1-2, 518 ms for 3-4, 510 ms for 6-7, and 507 ms for 8-9). However, no other effects were significant. In particular, there was no interaction of response hand by parity, *F* (1, 39) = 1.137, *p* = .293, *MSE* = 2130, η_p^2 = .028. As we did not find evidence of a MARC effect masking the SNARC effect across the remaining studies, we do not report any further MARC analyses.

Table 1. Mean reaction times (ms), standard deviations and presence of SNARC effect across all experiments.

Experiment	Mean reaction time (SD)	SNARC effect
Experiment 1 – Color decision	447 ms (66)	No
Experiment 2 – Go / no-go color decision	511 ms (92)	Yes
Experiment 3 – Color decision to digits (mixed stimulus onset)		
0 ms color onset	474 ms (52)	Yes
200 ms color onset	428 ms (43)	Yes
400 ms color onset	419 ms (47)	Yes
Experiment 4 – Color decision to circles (mixed stimulus onset)		
0 ms color onset	466 ms (65)	No
200 ms color onset	427 ms (66)	No
400 ms color onset	414 ms (55)	No
Experiment 5 – Color decision to digits (blocked stimulus onset)		
0 ms color onset	427 ms (69)	No
200 ms color onset	418 ms (51)	Yes
400 ms color onset	420 ms (60)	Yes

Discussion

There was no SNARC effect for simple color decisions to digits in Experiment 1, a finding consistent with Fias et al. (2001) and Lammertyn et al. (2002). However, when the task required participants to recognise the stimulus as a digit prior to making a response (in Experiment 2), there was a significant SNARC effect. The simplest explanation for this pattern of findings relates to the depth to which the stimulus must be processed in order to complete the task. While a straightforward color decision does not require access to any information about the digit, the requirement to recognise the stimulus as a digit in Experiment

2 was enough to trigger access to magnitude and its associated semantic information. Taken together, these results would suggest that at least some requirement to process numerical information (but not necessarily magnitude) is required to trigger the SNARC effect. This need not be so substantial as its parity status, but it does require at least recognition that the stimulus represents numerical information.

The differences between Experiment 1 and 2 are not limited to the recognition of the digit, however. Most obviously, Experiment 2 involves a more complex task than Experiment 1, and this is reflected in the reaction times; reaction times in Experiment 1 (447 ms) were significantly faster than Experiment 2 (511 ms), t (78) = 3.61, p < .001, d = .807, CI[-100.041, -28.909]. It is therefore possible that the simple color decision required in Experiment 1 was so easily and rapidly executed that it did not allow enough time for activated semantic information associated with the digit to impact on the pattern of response times.

There also remains the question of why at least one study in the literature has reported a positive SNARC finding for color decision; Hoffmann, Hornung, Martin, & Schiltz (2013) found a SNARC effect for color decision in children with a mean age of 5.84 years. This is a surprising finding given that other studies have not found an effect for color decision in adults, and also because other studies in children have found that the SNARC effect emerges at a later age in other tasks (e.g., Berch et al., 1999; van Galen & Reitsma, 2008; although cf. Yang et al., 2014). Indeed, Hoffmann et al. did not find a SNARC effect for magnitude decision in the same participants, and it is odd that the same children would show a SNARC effect for color (where magnitude is irrelevant to the task) but not for magnitude decisions (where magnitude clearly *is* relevant to the task). The key difference between Hoffmann et al.'s study and those run with adults (i.e., Fias et al., 2001; Lammertyn et al., 2002; Experiment 1 of the current studies) was that Hoffmann et al. displayed the digit in black for

200 ms before color onset. As such, it may be that viewing time is important in determining whether or not a SNARC effect occurs. In order to investigate this possibility, in Experiments 3 and 4 we introduced three color onset conditions.

Given the finding from Experiment 2 that SNARC effects can occur for color decision to digits, we additionally investigated whether the same could be true for other representations of magnitude. In Experiment 4, we presented participants with arrays of between one and nine circles, but manipulated the onset of color. If the SNARC effect really does index the existence of an automatic pathway to an amodal semantic representation, then we would predict that, whatever the pattern of SNARC effects cross the SOAs, it should be similar for digits and non-symbolic displays of numerosity.

In Experiment 3, participants made color decisions to digits with three onset conditions (0 ms, 200 ms and 400 ms). In the 0 ms onset condition, the digits appeared blue or green on the screen and participants responded to the color. However, in the 200 ms onset and 400 ms onset conditions, the digits appeared in black for 200 ms and 400 ms respectively before changing color. In Experiment 4, the procedure was exactly the same except that arrays of one to nine circles were displayed instead of digits.

Experiments 3 and 4

Method

Participants. Twenty participants (10 men, mean age 22.60 years, SD = 2.80) took part in Experiment 3 and twenty participants (12 men, mean age 21.30 years, SD = 1.78) took part in Experiment 4. All were undergraduate students recruited on a voluntary basis. All had normal or corrected-to-normal vision.

Stimuli, Design and Procedure.

Experiment 3 stimuli. The stimuli were black, blue and green digits (1-9, excluding 5) presented onscreen in Arial font size 36. There were three conditions; 0 ms color onset (the digit appeared in either blue or green), 200 ms color onset (the digit appeared in black for 200 ms before changing to either blue or green), and 400 ms color onset (the digit appeared in black for 400 ms before changing to either blue or green).

Experiment 4 stimuli. The stimuli were arrays of black, blue and green circles (1-9, excluding 5, presented onscreen). The total surface area of the circles in each array was 452 mm^2, with the surface area of individual circles varied within this. As with Experiment 3, there were three conditions; 0 ms color onset (the array of circles appeared in either blue or green), 200 ms color onset (the circles appeared in black for 200 ms before changing to either blue or green), and 400 ms color onset (the circles appeared in black for 400 ms before changing to either blue or green). An example of the stimuli used in Experiment 4 is shown in Figure 2.

Experiment 3 Design and Procedure. Participants were instructed that they should indicate whether the digit was presented in blue or green. Half of the participants responded to blue stimuli with the *M* key and green stimuli with the *Z* key; for the other half, the response mapping was reversed. In the 0 ms onset condition, on each trial a fixation cross was presented centrally for 1000 ms, and was then replaced by a blue or green digit, which remained onscreen for 2000 ms or until the participant made a response. This was followed by a blank screen for 1000 ms before the fixation point for the next trial. In the 200 ms onset condition, the sequence was identical except that after the fixation cross, the digit appeared in black for 200 ms before changing to either blue or green. In the 400 ms onset condition, the digit appeared in black for 400 ms before changing to either blue or green.

The experimental session consisted of 384 trials in total split across four blocks; each digit appeared 48 times, and 16 times in each onset condition. The presentation order of the digits and the onset conditions was randomised such that each block contained a mix of stimulus onsets. The experimental blocks were preceded by a practice block of 12 trials, with feedback on accuracy and reaction time. There was no feedback during the experimental blocks. The experimental stimuli were presented on a Dell 19” flat panel monitor using a Dell PC running Windows 7, with key presses recorded from a Dell keyboard. Reaction times were collected using E-Prime 2.0 software.

Experiment 4 Design and Procedure. The design and procedure for Experiment 4 was identical to Experiment 3 in all aspects other than that the participants were told that they would be responding to the color of arrays of circles.

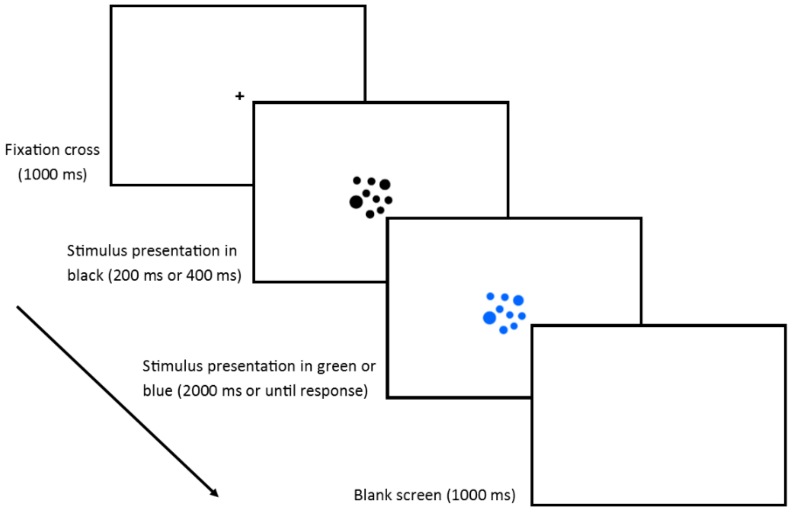

Figure 2. The time course of stimulus presentation in Experiment 4. In the 0 ms condition, the array of circles appeared immediately as either green or blue. In the 200 ms and 400 ms condition (pictured), the array of circles appeared in black first and then changed to green or blue 200 ms or 400 ms later. The stimulus pictured is a nine-circle array.

Results

Experiment 3 Results. The mean error rate was 3.21%. The mean reaction time across the conditions was 440 ms. A one-sample *t*-test revealed that, collapsed across all onset conditions, the regression weight differed significantly from 0, mean β = -.347, *t* (19) = -4.223, $p < .001$, *d* = .944, 95% CI [-.519, -.175], BF_{10} = 71.979. This remained true for each of the onset conditions when considered separately; 0 ms onset, mean β = -.275, *t* (19) = -3.054, *p* = .007, *d* = .683, 95% CI [-.464, -.087], BF_{10} = 7.320, 200 ms onset, mean β = -.310, *t* (19) = -4.003, $p < .001$, *d* = .895, 95% CI [-.472, -.148], BF_{10} = 46.441, and the 400 ms onset, mean β = -.258, *t* (19) = -3.126, *p* = .006, *d* = .699, 95% CI [-.431, -.085], BF_{10} = 8.373. A repeated measures analysis of variance (ANOVA) revealed no significant effect of color onset (0 ms versus 200 ms versus 400 ms) on the regression weight, *F* (2,38) = .107, *MSE* = .130, *p* = .898, η_p^2 = .006. The mean response time differences across conditions are displayed in Figure 3.

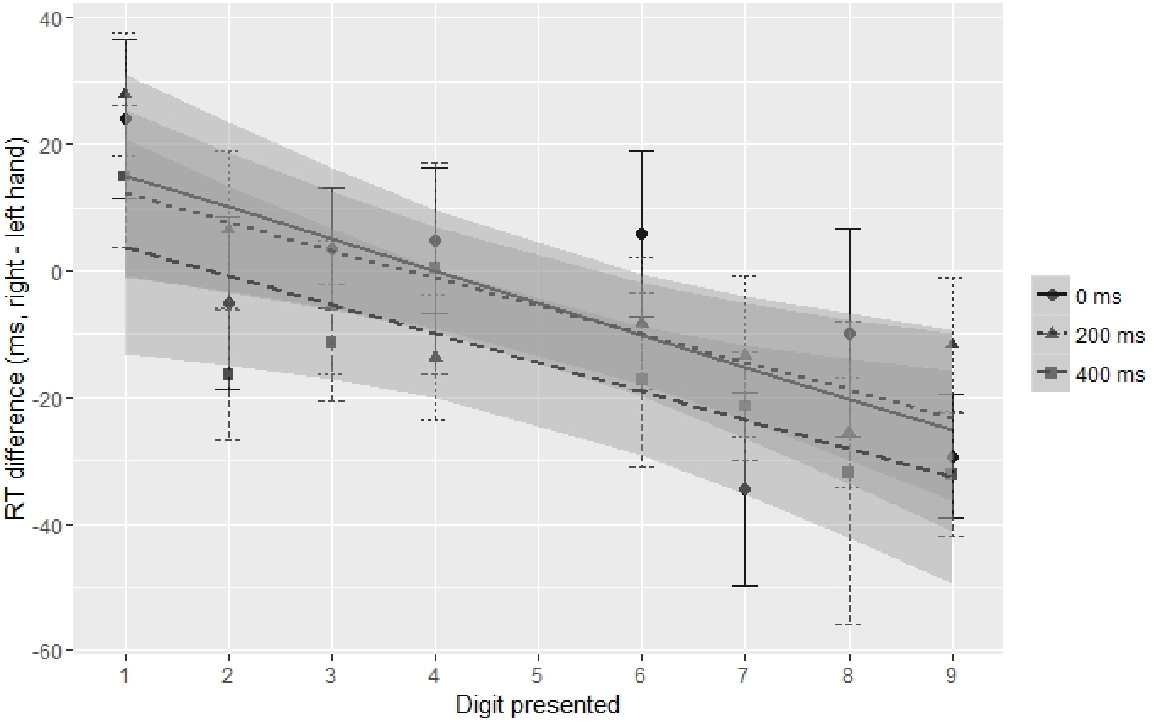

Figure 3. Mean reaction time difference for each digit for color decision in Experiment 3 for the 0 ms, 200 ms, and 400 ms color onset conditions. Errors bars show +/- 1 standard error. The shaded area shows the 95% confidence interval for the trend line.

A repeated measures ANOVA revealed that color onset (0 ms versus 200 ms versus 400 ms) had a significant effect on reaction times, F (2,38) = 89.264, MSE = 190.708, p <.001, η_p^2 = .825. Pairwise comparisons revealed that this was because the mean reaction time for the 0 ms onset condition (474 ms, SD = 52) was significantly slower than the reaction time for the 200 ms onset condition (428 ms, SD = 43), p < .001, which was significantly slower than the reaction time for the 400 ms onset condition (419 ms, SD = 47), p = .035.

Experiment 4 Results. The mean error rate was 6.03%. The mean reaction time across the conditions was 436 ms. A one-sample *t*-test revealed that the regression weight did not differ significantly from 0 across the conditions, mean β = .038, t (19) = .426, p = .675, d = .095, 95% CI [-.149, 0.226], BF_{10} = 0.252. This remained true for each of the onset conditions when considered separately; 0 ms onset, mean β = -.10, t (19) = -1.101, p = .285, d = .246, 95% CI [-.29, .09], BF_{10} = 0.396, 200 ms onset, mean β = -.093, t (19) = -.983, p = .338, d = .220, 95% CI [-.291, .105], BF_{10} = 0.356, and the 400 ms onset, mean β = -.026, t (19) = -.283, p = .780, d = .063, 95% CI [-.215, .164], BF_{10} = 0.241. A repeated measures analysis of variance (ANOVA) revealed no significant effect of color onset (0 ms versus 200 ms versus 400 ms) on the regression weight, F (2,38) = .202, MSE = .166, p = .602, η_p^2 = .015. The mean response time differences across conditions are displayed in Figure 4.

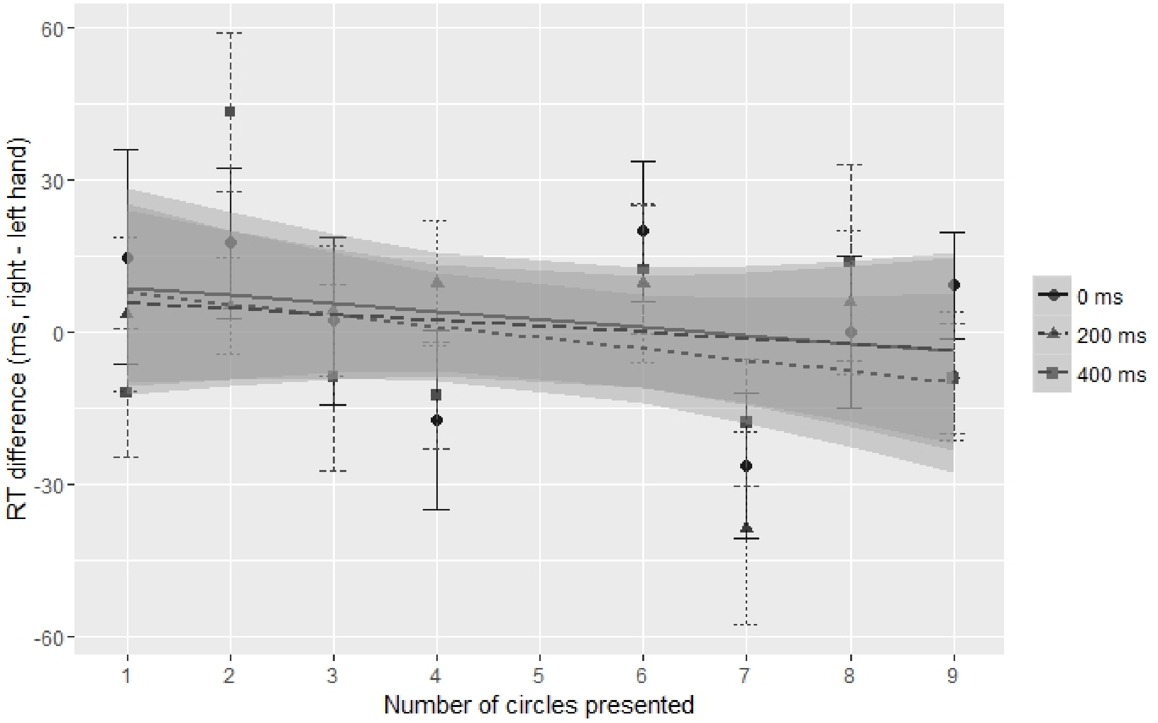

Figure 4. Mean reaction time difference for each numerosity for color decision in Experiment 4 for the 0 ms, 200 ms, and 400 ms color onset conditions. Errors bars show +/- 1 standard error. The shaded area shows the 95% confidence interval for the trend line.

A repeated measures ANOVA revealed that color onset (0 ms versus 200 ms versus 400 ms) had a significant effect on mean RTs, *F* (2,38) = 47.67, *MSE* = 310.95, *p* <.001, η_p^2 = .715. Pairwise comparisons revealed that this was because the mean reaction time for the 0 ms onset condition (466 ms, SD = 65) was significantly slower than the reaction time for the 200 ms onset condition (427 ms, SD = 66), *p* < .001, which was significantly slower than the reaction time for the 400 ms onset condition (414 ms, SD = 55), *p* = .040.

Discussion

In Experiment 3, there was a SNARC effect for color decision regardless of the stimulus onset. Indeed, the β-weight for the 0 ms onset (-.275) was similar to the 200 ms onset (-.310) and 400 ms onset (-.258). However, the mean reaction time across the different conditions did vary, with reaction times to the 0 ms condition (474 ms) slower than the reaction times to the 200 ms and 400 ms conditions (428 ms and 419 ms respectively, see Table 1). In contrast, there was no evidence whatsoever of a SNARC effect for color decision to non-symbolic number in Experiment 4, despite the fact that the mean reaction times across the conditions were very similar to those in Experiment 5 (466 ms, 427 ms, and 414 ms for the 0 ms, 200 ms, and 400 ms conditions respectively, see Table 1). Our results are consistent with the conclusion that the form of number representation is important in determining whether or not the SNARC effect occurs; this will be considered in detail in the General Discussion.

The increase in reaction time for the 0 ms condition is likely due to the temporal uncertainty of the color onset; indeed, the reaction time pattern is reminiscent of the fore-period effect where reaction times are longer when the interval between a warning stimulus and an imperative stimulus is shorter (Woodrow, 1914; see e.g., Los, 2010 for a review); however note that foreperiod effects occur over a longer time frame (in the order of seconds rather than hundreds of milliseconds). It seems likely that temporal uncertainty has introduced an element of inhibition to the task; over the course of the experiment, participants must suppress the urge to respond immediately upon seeing the digit because on two-thirds of the trials they will not be able to make a response. Whether because of the inhibitory component, or purely because their reaction times are slower, this triggers a SNARC effect in the 0 ms condition for digits. More informatively, the reaction times to the 200 ms and 400 ms onset conditions in Experiment 3 (as timed from color onset), were faster than reaction times in Experiment 1 for simple color decision (428 ms and 419 ms respectively versus 447 ms). Despite the speed with which participants were able to perform the color task in these conditions, they still showed a SNARC effect.

The finding of a SNARC effect for color decision in Experiment 3 is consistent with Hoffmann et al.'s (2013) SNARC finding in children, but the mixed presentation of onset conditions means that it is difficult to know the relative contribution of viewing time versus uncertainty around color onset. In order to address this, in Experiment 5 participants again made color decisions to digits in the 0 ms, 200 ms and 400 ms color onset conditions. However, the conditions were now blocked according to color onset. In other words, every participant completed a block of 0 ms onset trials, a block of 200 ms onset trials, and a block of 400 ms onset trials (with the order counterbalanced across participants). If the SNARC effect observed in Experiment 3 was triggered by temporal uncertainty, we would expect to see no SNARC effect in any of the blocks in Experiment 5. However, following the hypothesis that viewing time was important, we hypothesised that we would find no SNARC effect in the 0 ms condition, but a significant SNARC effect in the 200 ms and 400 ms conditions. As there was no SNARC effect observed across any of the conditions in Experiment 4, we did not run a parallel study using arrays of circles.

Experiment 5

Method

Participants. As we were potentially interested in block order as well as the effect of onset condition, and in order to counterbalance block order completely, we increased the number of participants in Experiment 5. Eighty-four participants (16 men, mean age 20.77 years, SD = 2.87) took part. All were undergraduate students recruited on a voluntary basis. All had normal or corrected-to-normal vision.

Stimuli, Design and Procedure. The stimuli were identical to Experiment 3. As in Experiments 3 and 4, there were three color onset conditions; 0 ms color onset (the digit appeared in either blue or green), 200 ms color onset (the digit appeared in black for 200 ms before changing to either blue or green), and 400 ms color onset (the digit appeared in black for 400 ms before changing to either blue of green). However, unlike in Experiments 3 and 4, the presentation of these conditions was blocked such that each participants saw three blocks (0 ms color onset, 200 ms color onset, and 400 ms color onset) with the order of block presentation counterbalanced across participants.

Participants were instructed that they should indicate whether the digit was presented in blue or green. Half of the participants responded to blue stimuli with the *M* key and green stimuli with the *Z* key; for the other half, the response mapping was reversed. The experimental session consisted of three blocks of 128 trials; within each block, each digit appeared 16 times (eight times in green and eight times in blue). One block had a color onset of 0 ms for all trials, one had a color onset of 200 ms and the other had a color onset of 400 ms. The order of these blocks was counterbalanced across participants; as there were six possible block orders (0-200-400, 0-400-200, 200-0-400, 200-400-0, 400-0-200, 400-200-0), each potential block order was seen by 14 participants. The experimental sessions were preceded by a practice session of 12 trials with four 0 ms color onset trials, four 200 ms color onset trials, and four 400 ms color onset trials presented sequentially. In the practice block, participants were given feedback on accuracy and reaction time but there was no feedback in the experimental blocks. Prior to the practice session, participants were told “in some blocks of the experiment, the number will appear in black before changing color. You should wait until it changes color before making your response. In other blocks the number will just appear as blue or green immediately. You will see examples of both types of trial in the practice session, but in the experiment itself you will only see one type of trial in each block”. The participants were not told prior to each block which condition they would be seeing. The experimental stimuli were presented on a Dell 19” flat panel monitor using a Dell PC running Windows 7, with key presses recorded from a Dell keyboard. Reaction times were collected using E-Prime 2.0 software.

Results

The mean error rate was 3.38%. The mean reaction time was 423 ms. A one-sample *t*-test revealed that, collapsed across all conditions, the regression weight differed significantly from 0, mean β = -.200, *t* (83) = -5.019, *p* < .001, *d* = .548, CI [-.279, -.121], BF_{10} = 5279.647. However, when considered separately, there was a significant effect for the 200 ms onset, mean β = -.126, *t* (83) = -2.879, *p* = .005, *d* = .314, CI [-.213, -.039], BF_{10} = 5.554, and the 400 ms onset, mean β = -.238, *t* (83) = -6.56, *p* < .001, *d* = .716, CI [-.310, -.166], BF_{10} = 2.562e+6. but not the 0 ms onset, mean β = -.068, *t* (83) = -1.41, *p* = .162, *d* = .154, CI [-.163, .028], BF_{10} = .312. Indeed, a repeated measures ANOVA revealed a main effect of color onset, *F* (2, 166) = 4.249, *MSE* = .147, *p* = .016, η_p^2 = .049. Pairwise comparisons revealed that the SNARC effect for the 400 ms condition (-.238) was significantly greater than for the 0 ms condition (-.068), *p* = .015. In order to assess whether the lack of a SNARC effect in the 0 ms block was influenced by block order, we ran a one-way ANOVA on the 0 ms color onset condition with block (first versus second versus third) as a factor. The SNARC effect for the 0 ms block did not vary depending on block order, *F* (2, 81) = .118, *p* = .889. The mean β-weight for the 0 ms condition when it was the first block was -.096, when it was second it was -.070 and when it was third it was -.038. The mean response time differences across conditions are presented in Figure 5.

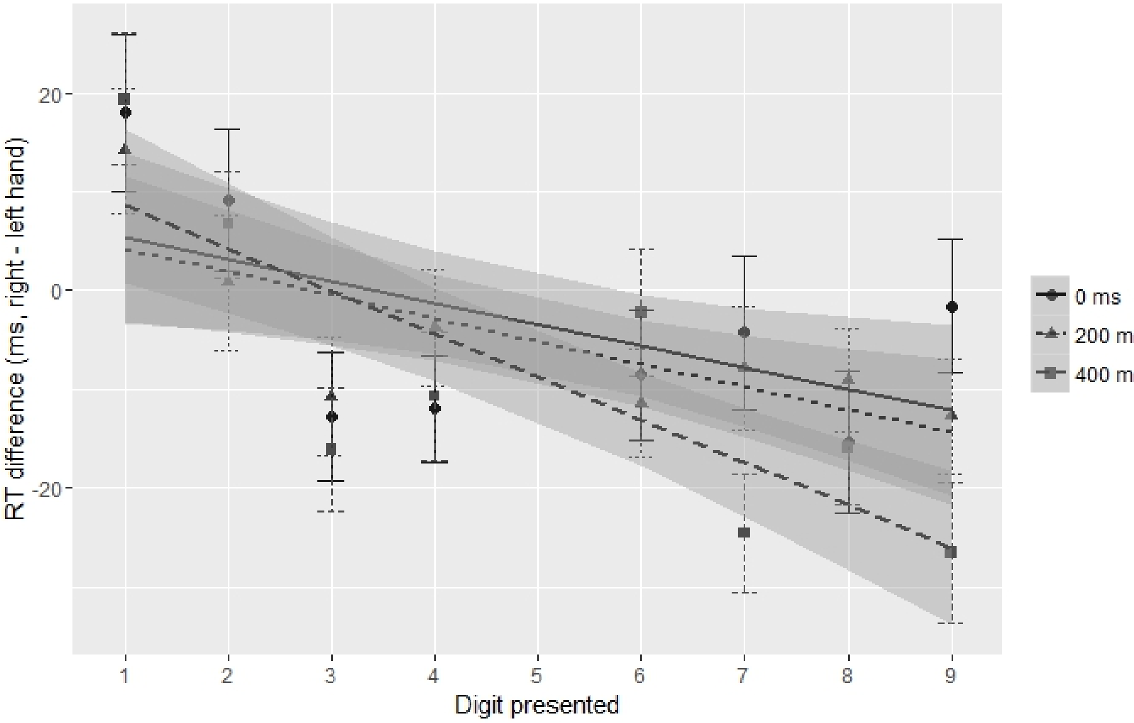

Figure 5. Mean reaction time difference for each digit for color decision in Experiment 5 for the 0 ms, 200 ms, and 400 ms color onset conditions. Error bars show +/1 standard error. The shaded area shows the 95% confidence interval for the trend line.

A repeated measures ANOVA on mean reaction times revealed no effect of color onset condition, *F* (2,166) = 2.446, *MSE* = 739.161, *p* = .090, η_p^2 = .029. The mean reaction time for the 0 ms condition was 427 ms, for the 200 ms condition it was 418 ms, and for the 400 ms condition it was 420 ms.

Discussion

In Experiment 5, we found a mixed pattern of SNARC effects for digits; participants showed a SNARC effect in the 200 ms and 400 ms onset conditions, but not in the 0 ms onset block. This was despite the fact that (unlike in Experiments 3 and 4 when onset was mixed), the mean reaction time to the colored digit did not differ significantly across the conditions. Our results are consistent with the conclusion that the act of viewing the digit for 200 ms or

400 ms before making a response is sufficient to trigger magnitude information associated with that digit, and hence its spatial associations. Furthermore, they are consistent with the hypothesis that the SNARC effect for the 0 ms condition in Experiment 3 was triggered by the temporal uncertainty of color onset.

General Discussion

The current set of experiments was designed to investigate the extent to which magnitude information and its spatial associations are automatically accessed upon presentation of numerical information, and whether the form of that numerical information matters. To summarise, we found no evidence of a SNARC effect for simple color decisions to digits (Experiment 1, and the 0 ms onset condition in Experiment 5). However, we did find a SNARC effect when participants had to recognise a stimulus as a digit prior to responding to the color (Experiment 2). Additionally, we found a SNARC effect for color decision to digits when the participant viewed the digit for 200 ms or more before color onset (Experiments 3 and 5), or if there was temporal uncertainty regarding the onset of color (Experiment 3). We observed no evidence of a SNARC effect for color decisions to non-symbolic representations of number, regardless of how long the participant viewed the stimulus before color onset, or whether there was temporal uncertainty regarding color onset (Experiment 4). There did not appear to be an obvious relationship between the speed of participants' responding and the presence or absence of the SNARC effect (see Table 1).

Automaticity of the SNARC effect for symbolic number

The SNARC effect has been discussed in terms of both ends of what we might call the automaticity spectrum. To return to the examples in the Introduction, we can contrast statements such as "mere observation of numbers obligatorily activates the spatial representations associated with meaning" (Fischer et al., 2003, p. 556) with "the mental number line is not activated automatically but at best only when contextually relevant"

(Zanolie & Pecher, 2014, p. 1). In reality, our findings suggest that neither of these statements are strictly true. These two examples map nicely onto the distinction we drew in the Introduction between autonomous and intentional automaticity (e.g., Cohen Kadosh et al., 2008; Tzelgov & Ganor-Stern, 2005; Tzelgov et al., 1996); to reiterate briefly, processes that are autonomously automatic occur regardless of whether they are part of the task requirement and processes that are intentionally automatic occur *only* when they are part of the task requirement. The findings of the current studies suggest that activation of magnitude information and its spatial associations falls somewhere between these two possibilities (at least, for symbolic representations of number); certainly, it does not meet the strictest requirements of autonomous automaticity as it does not occur for color decisions under the most straightforward circumstances (simple binary color decisions). It meets the requirements for intentional automaticity in that it occurs for tasks when a minimal amount of numerical processing is necessary (Experiment 2) and yet, it must fall somewhere between the two ends of the spectrum, as it also occurs for tasks where numerical information is not part of the task requirement (Experiments 3 and 5). Indeed, we would argue that the pattern of results suggests that the SNARC effect is closer to autonomous than intentional automaticity.

In a wide-ranging analysis of the nature of automaticity, Moors and De Houwer (2006) recommended diagnosing automaticity by examining the presence of its various features. There are a number of these that the current studies address. Firstly, we can rule out a “purely stimulus driven” account; in Experiment 1 and Experiment 5 (see the 0 ms onset), mere exposure to a digit was not sufficient to cause a SNARC effect. However, if we look at features that would be classified as “goal-related” (Moors and De Houwer include (un)intentional, goal-directed, goal (in)dependent, (un)controlled/(un)controllable, and autonomous under this bracket), our results are more consistent with the stronger end of an automaticity continuum. Numerical magnitude was not relevant to the task in any of our experiments, however numerical status *was* relevant in Experiment 2 (where the digit had to be recognised as a number). We can argue then that the act of recognising a stimulus as a number is sufficient to trigger access to numerical magnitude regardless of whether it is relevant to the task. Furthermore, the finding of a SNARC effect in Experiment 3 and in Experiment 5 (in the 200 ms and 400 ms onset conditions) suggests that numerical status itself is not a necessary trigger for the SNARC effect.

One aspect of automaticity identified by Moors and De Houwer (2006) is that a process should be *fast*. This is relevant for the current studies; while the presence of the SNARC effect was not related to reaction time to color onset, it *was* related in part to the length of time for which the participant viewed the digit prior to making a response. So, in Experiment 5, the reaction times across the 0 ms, 200 ms and 400 ms conditions from color onset were 427 ms (no SNARC effect), 418 ms (SNARC effect) and 420 ms (SNARC effect) respectively. However, if we take reaction times from first presentation of the digit, the same values are 427 ms, 618 ms, and 820 ms. One might then argue that access to numerical magnitude is just relatively slow and was not completed in time to interfere with reaction time in the 0 ms condition. However, this cannot be the only account of our effects, as the reaction time from digit onset in Experiment 3 were 474 ms, 628 ms, and 819 ms in the 0 ms, 200 ms, and 400 ms conditions respectively and yet the SNARC effect was comparable across the three conditions. Furthermore, we should take into account that Fias et al. (2001) pushed color decision reaction times to 490 ms by making the color discrimination more difficult and yet still did not find a SNARC effect.

We believe that Experiment 3's findings suggest that simply the act of having to inhibit a response is a sufficient trigger for the SNARC effect. Indeed, it may be possible to account for this pattern of findings using Fias et al.'s (2001) neural overlap account. Fias et al. found a SNARC effect for orientation decisions to rotated digits but not color decisions and explained their findings according to the extent to which information from visual features is processed by the parietal pathway; while orientation depends on the parietal cortex, color processing is not thought to substantially rely on these areas (e.g., Chao & Martin, 1999; Faillenot, Sunaert, Van Hecke, & Orban, 2001; Murata, Gallese, Luppino, Kaseda, & Sakata, 2000). Crucially, the parietal cortex is thought to be activated for coding spatial representations of numerical quantity from number digits, number words, and non-symbolic displays of dot patterns (e.g., Ansari, Dhital, & Siong, 2006; Cutini, Scarpa, Scatturin, Dell'Acqua, & Zorzi, 2014; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Eger, Sterzer, Russ, Giraud, & Kleinschmidt, 2003; Gebuis, Cohen Kadosh, de Haan, & Henik, 2009; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004; Pinel, Piazza, Le Bihan, & Dehaene, 2004; see Hubbard et al., 2005; Nieder & Dehaene, 2009 for reviews). As such, Fias et al. argued that irrelevant information regarding the magnitude of the digit (and hence its position on the mental number line) interfered with processing orientation. Using this logic, one might argue that the necessity to inhibit responses on symbol trials in Experiment 2 would recruit prefrontal resources, which are part of the circuit recruited for the processing of numerical information and ordinal sequences more generally (e.g., van Opstal, Fias, Peigneux, & Verguts, 2009). Furthermore, executive control functions (which include inhibition) are subserved by multiple neural circuits involving interconnections of the prefrontal cortex with striatal and parietal regions (e.g., Edin et al., 2009). In other words, one could argue that the temporal uncertainty in Experiment 3, and the requirement to withhold a response until color onset in the 200 ms and 400 ms conditions in Experiment 5 could be enough to trigger an inhibitory component to the task and so prompt a SNARC effect (note that this explanation is also consistent with the SNARC effect for the go / no-go task in Experiment 2).

In terms of setting the current findings within the broader context of SNARC effects, the majority of reported studies use tasks that involve processing of semantic information about number. At the extreme end of this are studies that ask people to make magnitude decisions (e.g., Hedge, Powell, & Sumner, 2017), but the parity decision task (probably the most commonly used SNARC task) also requires retrieval of semantic information regarding the number that is likely to then also trigger access to magnitude. There are fewer studies that use tasks where numerical information is entirely irrelevant to the task goal. One example is visual detection (Fischer et al., 2003); however, as reported in the Introduction, this was not replicated by Zanolie and Pecher (2014) except when magnitude was task-relevant. Interestingly, Bulf et al. (2014) used this paradigm and compared symbolic and non-symbolic number, finding a SNARC effect for both, but they only used the digits and numerosities 2 and 9 as stimuli. It is possible that the use of only two numerical magnitudes influenced participants' approach to the task. Further research will be needed to establish whether the visual detection paradigm reliably produces SNARC effects; indeed, there is currently a multi-lab registered replication ongoing to this effect (Colling & Holcombe, 2017). Another example often cited as evidence for the SNARC effect's automaticity is the phoneme monitoring task (Fias et al., 1996). On the face of it, the phoneme monitoring task might seem to provide only weak triggers to numerical magnitude; however, the task used involves responding to Arabic digits. In other words, in order to report whether or not the digit contained the /e/ phoneme, participants had to transcode the stimuli from a visually presented digit to a verbal representation of the number, a process that Fias et al. argued was likely to involve accessing the semantic number system. In this respect, the phoneme monitoring task bears some resemblance to our go / no-go task in Experiment 2; it does not require processing of numerical magnitude, but it *does* require access to numerical information of a sort, and in both cases this appears to be sufficient to trigger the SNARC effect.

Modality dependence of the SNARC effect

There was no evidence whatsoever for a SNARC effect for non-symbolic number in Experiment 4, and this raises some interesting questions. To our knowledge, the only other reported SNARC effects for non-symbolic number when magnitude was irrelevant to the task are Mitchell et al. (2012), who reported a SNARC effect for orientation decisions to triangles, and Bulf et al. (2014), who used a visual detection task (discussed above). However, in our own lab we have failed to replicate the SNARC effect for orientation decisions three times (Cleland, Corsico, White & Bull, in prep). In terms of the automaticity of access to magnitude and its spatial associations, therefore, the emerging picture appears to be that non-symbolic number does not provide the same direct and automatic route that symbolic number does.

In many ways, this is a surprising finding. If digits provide such a direct route to magnitude and its spatial associations, then why not non-symbolic number (which, by its very nature, provides a more explicit representation of magnitude)? After all, there is strong evidence that many animals have a “number sense” of sorts (see e.g., Brannon, 2005, for a review) and there is even evidence that some animals have a preference for left-to-right orientation of magnitude, including chimpanzees (e.g., Adachi, 2014) and birds (e.g., Rugani, Kelly, Szelest, Regolin, & Vallortigara, 2010; Rugani, Vallortigara, Priftis, & Regolin, 2015; see Rugani, Vallortigara, & Regolin, 2015, for a review).

There are a couple of issues that need to be addressed here. The first is that the non-symbolic stimuli in Experiment 4 contain many non-numerical cues to magnitude that do not play a role in digit processing (e.g., individual item area, item spacing, convex hull, total surface area). In order to minimise the contribution of non-numerical cues to magnitude, the stimuli in Experiment 4 were controlled for aggregate surface area and, so far as possible, the area subtended by the stimulus. As a result of this, the surface area of any individual items in the 9-circle array would be vastly reduced compared to the surface area of the circle in the 1-

circle array. As such, properties of the stimuli that would usually provide quick and easy visual cues to overall number were in fact *in*congruent with magnitude. There is an increasing body of evidence to suggest that these visual cues are important for determining performance on numerical processing tasks (see e.g., Gebuis, Cohen Kadosh, & Gevers, 2016; Gebuis & Reynvoet, 2012). Furthermore, this appears to hold for tasks with a spatial component; Cleland and Bull (2015) reported that participants performing a bisection task to a line flanked by numerosities were at least as influenced by subtended area and aggregate surface area as they were by number of items (participants performing this task on a line flanked by digits will bisect towards the numerically larger digit, e.g., Calabria & Rossetti, 2005; de Hevia, Girelli, & Vallar, 2006; Fischer, 2001). However, note that in our own lab, we have failed to replicate the finding of a SNARC effect for orientation decisions to triangles even when we allow the aggregate surface area of the triangles in the array and the subtended area to increase congruently with magnitude (Cleland et al., in prep). As such, even for the orientation decision task (which should show a SNARC effect based on the findings of Fias et al., 2001) and when all the visual cues are pointing towards increasing magnitude with increasing items, we still do not find a SNARC effect. It is therefore particularly surprising that Bulf et al. (2014) do report a SNARC effect for the visual detection task, which should provide a much weaker trigger to magnitude.

The second issue is that there is evidence that people are able to automatically extract quantity by means of a rapid and accurate subitizing (or “parallel individuation”) process for quantities less than five (e.g., Jevons, 1871; Kaufman, Lord, Reese, & Volkmann, 1949; Trick & Pylyshyn, 1994). Indeed, Mitchell et al. (2012) reported that the SNARC effect was strongest in the subitizing range (i.e., when only the 1-4 arrays were considered). Focussing on the subitizing range in Experiment 4 allows us to address both this issue and the issue of numerical cues. While the aggregate surface area (i.e., total space occupied by all the individual circles not including the spaces between them) was held constant across all conditions, the area subtended by the stimulus could only be controlled once there were enough items to spread the stimuli sufficiently; in other words, no amount of rearranging two circles can make them subtend the same area as nine circles. Therefore, the strongest test of a SNARC effect for non-symbolic number was to look at the 1-4 range. We therefore re-ran the analysis for the subitizing range only. However, we found no evidence of a SNARC effect overall, $\beta = -.136$, t (19) = -1.005, $p = .328$, $d = .225$, CI [-.416, .147], $BF_{10} = .363$. In fact, the SNARC effect was not significant in any of the onset conditions once multiple comparisons were taken into account: 0 ms onset, $\beta = -.313$, t (19) = -2.243, $p = .037$, $d = .502$, CI [-.605, -.021], $BF_{10} = 1.761$ (note that the Bayes Factor here suggests only anecdotal evidence for the hypothesis); 200 ms onset, $\beta = .046$, t (19) = .317, $p = .754$, $d = .071$, CI [-.257, .348], $BF_{10} = .243$; 400 ms, $\beta = -.087$, t (19) = -.746, $p = .465$, $d = .167$, CI [-.331, .157], $BF_{10} = .298$. In other words, even when non-symbolic number should have provided the most basic and direct access to magnitude information, we did not observe a SNARC effect.

So, why does non-symbolic number not trigger a SNARC effect when so many other forms of numerical representation do? One possibility relates to the fact that non-symbolic representations of number do not offer an easy and direct route to a verbal label, and that a verbal label may be necessary to elicit a SNARC effect. Indeed, accounts of the SNARC effect often make explicit reference to either verbal labels or coding (see section below). We therefore make two predictions for future experiments. The first is that placing people under conditions that prevent them from accessing verbal labels should attenuate or eliminate the SNARC effect. The second is that asking people to respond to non-symbolic representations of number that *do* have easy verbal labels will induce a SNARC effect; perhaps this explains why Bulf et al. (2014) find a SNARC effect for non-symbolic number using only arrays of two and nine dots; in this case, there is an easy distinction to be made between “few” and “many”.

Implications for accounts of the SNARC effect

Various accounts of the SNARC effect have been proposed, but they can be grouped into three categories corresponding to the mental number line account (e.g., Dehaene et al., 1993), strategic accounts (most notably the working memory account, e.g., van Dijck & Fias, 2011), and the polarity and conceptual coding accounts (e.g., Gevers, Verguts, Reynvoet, Caessens, & Fias, 2006; Proctor & Cho, 2006).

Dehaene et al. (1993) proposed that the SNARC effect reflected activation of a left-to-right oriented number magnitude or number line and discussed it within the framework of Dehaene’s (1992) triple-code model (cf. e.g., Dehaene & Cohen, 1995; Hubbard et al., 2005). They argued that the strong SNARC effect observed for visually displayed digits could be attributed to an automatic “Arabic-to-analogue” transcoding process. They observed a weakened SNARC effect for verbal numbers and argued that the verbal-to-analogue pathway was either less automatic or absent. This “mental number line” account is intuitively appealing, and is arguably the dominant framework within which SNARC effects are discussed in the literature. However, the pattern of positive and negative SNARC findings across the current experiments (and the wider literature) suggests that the mechanisms underlying the SNARC effect must be somewhat more complex than a straightforward automatic transcoding process.

Under strategic accounts of the SNARC effect, most notably the working memory account, visuo-spatial associations are short- rather than long-term and built during task execution (e.g., Fias, van Dijck, & Gevers, 2011; Fischer, 2006; Fischer, Mills, & Shaki, 2010; van Dijck & Fias, 2011; see Fias & van Dijck, 2016 for a review). These accounts are based on findings which demonstrate that there are spatial associations with ordinal information in working memory. For example, van Dijck and Fias (2011) showed that items presented at the beginning of a verbal working memory sequence were responded to faster and more accurately with the left hand than the right hand, whereas items presented towards the end were responded to faster and more accurately with the right hand. This effect occurred for both numerical and non-numerical stimuli (specifically, lists of fruit and vegetables, which we would not expect to have long-term spatial associations). On the basis of this finding, Van Dijck and Fias argued that participants performing a SNARC task encode the numbers presented during the experiment in working memory into a task-set that stores both the stimuli presented and the responses required (this being a strategy to aid task execution). The spatial association whereby small is associated with left and large with right arises because participants make use of the existing ordinal properties of number so that (e.g.) 1 precedes 2, which precedes 3, and so on. The SNARC effect reflects this temporary ordinal information.

The fact that the SNARC effect was inconsistent across different tasks in our study should, in theory, favour strategic accounts. For example, the lack of an effect in the non-symbolic task could simply be attributed to the fact that participants have no quick and easy verbal labels for the arrays of circles presented (at least, the arrays do not provide the quick and direct route to a verbal label that digits do). As such, they are less likely to be coded in working memory in an ordinal fashion. One could also argue that participants do not construct a task-set for simple color decision to a digit (i.e., Experiment 1 and the 0 ms condition in Experiment 5) because the task is so easy. However, an issue for the working memory hypothesis is the fact that the SNARC effect did not occur for the 0 ms onset condition in Experiment 5, regardless of whether it was the first, second or third block of the experiment. When the 200 ms or 400 ms block occurred first, under the Working Memory account, participants must have constructed a spatial coding during task execution that led to the SNARC effect in those blocks. What is unclear is why such a spatial coding would then be abandoned for the subsequent 0 ms block.

Under Proctor and Cho’s (2006) polarity account, differences in performance on a given task are driven by the coding of response alternatives as having positive or negative polarity along different dimensions; when there is polarity correspondence, then responses are faster. In the case of the SNARC effect specifically, a correspondence between magnitude polarity (large number +, small number -) with that of response polarity (right +, left -) drives the effect rather than any long-term spatial representations of number. It is not immediately clear how this account would fit with the mixed pattern of effects for color decision across the different tasks in the current studies, but Gevers, Verguts, Reynvoet, Caessens and Fias’s (2006) provide a well-specified computational conceptual coding account that does allow us to make more detailed predictions.

We would classify Gevers et al.’s (2006) computational model of the SNARC effect as a conceptual coding account, although it contains elements of the mental number line account as well. The model consists of three layers. Firstly, there is a bottom layer that represents the mental number line, with a number field (consisting of nodes for each number) and a standard field (a task dependent field that codes for the qualities of the digit relevant for the task). The second layer consists of a magnitude field (it is assumed that the number is always coded as small or large, regardless of the task), and additional fields that are activated dependent on the task (for example, a parity field that contains nodes for “even” and “odd”). In our study therefore, we would expect there to be a color field, with one node for blue and another for green. This middle layer receives input from both the number field and the standard field. For example, a blue “9” in our task would always activate the “large” node in the Magnitude field, and the “blue” response in the Color field. A final top layer contains nodes for left and right hands that are connected by lateral inhibition. These receive activation from both the Magnitude field and the relevant task field. Once one of these nodes reaches a fixed threshold, the corresponding response can be initiated. To take an example from our task, consider a blue digit “9” when blue responses are mapped to the left hand. At the middle layer, the “Larger” node in the Magnitude field is activated and inputs activation to the “Right hand” node in the top layer. However, the number field activates the “Blue” (corresponding to left) node for the color field in the middle layer and spreads activation to the “Left hand” node at the top layer. Thus, the Magnitude field activates the “Right hand” node, and the task-specific Color field activates the “Left hand” field, they inhibit one another and it takes some time for the “Left hand” to reach the threshold level before the response can be executed. This could be compared with a trial where the digit “1” appears in blue; in this case both the Magnitude and the Color field activate the “Left hand” field at the top layer and this quickly reaches threshold.

Crucially, this model predicts that the SNARC effect should increase with time; in their implementation of the model, Gevers et al. (2006) found that the slope of the SNARC effect became larger in slower conditions. In our studies, the presence or absence of the SNARC effect was not related to reaction time to color onset; however, as noted above, it *was* related to the length of time for which the participant viewed the digit prior to making a response. We believe that this could be consistent with Gevers et al.’s model if we assume that longer viewing time means more activation from the Magnitude field. The Magnitude field will be activated as soon as the digit is presented, while the Color field will not be activated until color onset. As such, on incongruent trials, the incorrect response at the top layer will be activated and inhibiting the correct response before the Color field has received input from the Number field; as a result it will take longer for the correct response to reach the threshold level. In contrast, on congruent trials, the correct response will already be activated at the top layer by the time the Color field provides its input and so it can rapidly reach the threshold level. We would therefore argue that the current findings are most consistent with this computational model.

Conclusion

Treisman, Vieira and Hayes (1992) wrote that “Perhaps we should think of [automaticity] like a medical syndrome with a set of symptoms: The more you have, the more fully automatized you are” (p. 341). Following this train of thought, we would argue that the SNARC effect has a serious case of automaticity; so far as digit processing is concerned, it is much easier to find a task that *does* trigger access to magnitude and its spatial associations than it is to find a task that does not. In the current series of studies we took one of the few tasks that has been reported not to show a SNARC effect (i.e., color decision) and found that even minor adjustments to the task conditions (i.e., a longer presentation time, temporal uncertainty, recognising the stimulus as a digit) were enough to trigger the effect. In other words, numerical magnitude and its spatial associations are accessed very readily upon presentation of a digit, with little additional triggering required. Conversely, we found no evidence whatsoever for a SNARC effect to non-symbolic representations of number, suggesting that, at the least, the SNARC effect for non-symbolic number lies very much at the opposite end of the automaticity continuum. Our findings are most supportive of conceptual coding accounts of the SNARC effect (e.g., Gevers et al., 2006).

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